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Impact of Imperfect Parameter Estimation on the Performance of Multi-User ARGOS Receivers

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***Abstract*—In this paper, we analyze the performance of Successive Interference Cancelation (SIC) receivers in the context of the ARGOS satellite system. Multi-user SIC receivers are studied in presence of imperfect estimates of signal parameters. We derive performance graphs that show the parameter ranges over which a successful demodulation of all users is possible. First, the graphs are derived in the context of perfect parameter estimation. Then, imperfect parameter estimation is considered. Erroneous estimations affect both the amplitude and the time delay of the received signal. Carrier frequencies are assumed to be accurately measured by the receiver. ARGOS SIC receivers are shown to be both robust to imperfect amplitude estimation and sensitive to imperfect time delay estimation.**

I. Introduction

ARGOS is a global satellite-based location and data collection system dedicated for studying and protecting the environment [1]. User platforms, each equipped with a Platform Transmitter Terminal (PTT), transmit data messages to a 850 km Low Polar Orbit (LPO) satellite [2]. ARGOS satellites receive, decode, and forward the signals to ground stations. All PTTs transmit in a 100 kHz bandwidth using different carrier frequencies. The central carrier frequency f_0 is 401.65 MHz. Due to the relative motion between satellites and platforms, signals transmitted by PTTs are affected by both a different Doppler shift and a different propagation delay. Thus, ARGOS satellites receive overlapping signals in both frequency and time domains. This induces Multiple Access Interference (MAI) that should be suppressed as much as possible. To tackle this problem, several Multi-User Detection (MUD) techniques have been proposed for the reception of synchronous and asynchronous users [3], [4]. In particular, the Successive Interference Cancelation (SIC) detector has been shown to offer a good optimality-complexity trade-off compared to other common approaches such as the Maximum Likelihood (ML) receiver [5], [6]. In an ARGOS SIC receiver, users are decoded in a successive manner, and the signals of successfully decoded users are subtracted from the waveform before decoding the next user. This procedure involves a parameter estimation step and the issue here consists in studying the impact of erroneous parameter estimates on the performance of ARGOS SIC receivers. Indeed, errors in signal parameter estimation lead to a performance loss in terms of Bit Error Rate (BER) [7]. In particular, the signal to noise ratio (SNR) per bit that is required to achieve a target BER in presence of erroneous parameter estimation is higher than the one required to achieve the same performance when the parameter estimation is perfect. The knowledge of this SNR loss is of crucial importance since one of the main objectives in the design of new ARGOS satellite receivers, is to increase the number of users processed by unit of time. The achievement of this objective depends on the available link margin at the receiver. The higher this margin, the better the receiver succeeds in demodulating several user signals. So, when part of the link margin is used to compensate imperfect parameter estimation, less margin is available for user decoding. The contribution of this paper is to propose a performance analysis according to several environments in order to decide whether it is possible to recover none, one, or several user messages in a noisy signal. These environments vary according to both channel and signal parameters. Channel parameters refer to the time, frequency and energy differences between two received signals whereas signal parameters refer to the amplitude, time delay, and carrier frequency of each received signal[1]. The performance analysis provides graphs that show the parameter ranges over which successful demodulation of several users is possible. This allows the identification of scenarios that meet the design constraints in terms of link budget. In particular, we analyze the reception of two users as a function of their time difference and their frequency shift. Moreover, we analyze the receiver performance on the weakest signal in presence of erroneous parameter estimation on the strongest signal. In this paper, we consider imperfect estimates of both signal amplitudes and time delays. Carrier frequencies are assumed to be accurately measured by the receiver.

The rest of the paper is organized as follows. Section II introduces the system architecture and the definition of performance losses. In section III, performance of SIC receivers is analyzed in presence of perfect parameter estimation and imperfect parameter estimates are considered in section IV. We conclude in section V.

[1]Actually, the estimation of the carrier wave should include the estimation of two parameters: frequency and phase.

II. Receiver Architecture and Definitions

A. System model

We consider a Binary Phase Shift Keying (BPSK) transmission of two ($K = 2$) asynchronous users with different received carrier frequencies $f_k = f_0 + \delta f_k$ where $k \in [1, K]$. The frequency shift δf_k includes both the transmission frequency of user k and the Doppler shift due to the relative motion between the PTT and the satellite receiver. The base band received signal can be written as:

$$r(t) = \sum_{k=1}^{K} \sum_{m=0}^{M-1} A_k b_k[m] h(t - mT - \tau_k) \exp(j2\pi f_k t) + n(t) \tag{1}$$

where M is the number of symbols per user message, A_k is the amplitude of user k, $b_k[m] \in \{-1, +1\}$ is the m^{th} transmitted symbol of user k, $h(t)$ is the unit energy signature waveform with a value of $1/\sqrt{T}$ over one symbol interval $[0, T]$ where T is the symbol period, τ_k is the time delay of user k, and $n(t)$ is a circularly symmetric complex Gaussian noise with variance $\sigma^2 = 2N_0$. We assume an ascending order of the time delays: $\tau_1 \leq \tau_2 \leq T$. Moreover, we have that $\tau_1 = 0$, and $\tau_2 = \tau$. So, the time difference between the two users is equal to the time delay of the second user. The Power Separation Ratio (PSR) between the two signals is defined as

$$PSR = E_{b_1}/E_{b_2} \tag{2}$$

where E_{b_k} is the mean energy received per bit for user k. Throughout this paper, we assume perfect estimation of the received carrier frequencies f_k.

B. SIC Receiver

We first note that (1) can be written

$$r(t) = \sum_{k=1}^{K} r^{(k)}(t) + n(t)$$

where $r^{(k)}(t)$ is the signal with the k^{th} strongest power. We have that

$$r^{(k)}(t) = \sum_{m=0}^{M-1} A^{(k)} b^{(k)}[m] h(t - mT - \tau^{(k)}) \exp(j2\pi f^{(k)} t)$$

where $A^{(k)}$, $\tau^{(k)}$, $f^{(k)}$, and $b^{(k)}[m]$ are, respectively, the amplitude, time delay, carrier frequency, and m^{th} bit of the user with the k^{th} strongest signal. The signal $r(t)$ is first fed into a conventional detector [6], which demodulates the strongest signal in the presence of interferences. The symbols $\hat{b}^{(1)}[m]$ of $r^{(1)}(t)$ for $m \in [0, M-1]$ are decoded. Then the signal amplitude $\hat{A}^{(1)}$ and the time delay $\hat{\tau}^{(1)}$ are estimated in order to obtain a replica $\hat{r}^{(1)}(t)$. So, we have that

$$\hat{r}^{(1)}(t) = \sum_{m=0}^{M-1} \hat{A}^{(1)} \hat{b}^{(1)}[m] h(t - mT - \hat{\tau}^{(1)}) \exp(j2\pi f^{(1)} t)$$

The estimated signal $\hat{r}^{(1)}(t)$ is then subtracted from the received signal $r(t)$. The resulting signal $s_1(t) = r(t) - \hat{r}^{(1)}(t)$ is fed into a second conventional detector to demodulate the weakest signal. In a first time, we assume perfect parameter estimation of the strongest signal, i.e. $\hat{A}^{(1)} = A^{(1)}$ and $\hat{\tau}^{(1)} = \tau^{(1)}$. Then, we consider imperfect estimation of these two parameters and we analyze the impact of imperfect estimation on the demodulation of the weakest signal.

C. Demodulation Condition

Due to the presence of MAI, the required SNR per bit to decode a specific user is inevitably higher than the one required when only one user is received. Let BER_{ref} be the reference BER corresponding to the nominal performance of an ARGOS receiver in the single user case. Let $(E_b/N_0)_{\text{ref}}$ be the reference E_b/N_0 ratio in order to achieve the reference BER, where E_b denotes the mean energy received per bit in the single user case. We define a demodulation condition: user p is successfully demodulated among a set of K users if its BER is less than or equal to BER_{ref}. Let p and q be the two received users, $p \in [1, K]$, $q \in [1, K]$ and $p \neq q$. When there are at most two users ($K = 2$), there are three possible cases for user reception:

- Case 1: the two signals are successfully demodulated.
- Case 2: only one signal is successfully demodulated.
- Case 3: none of the two signals is demodulated.

We should study the occurrence of these cases according to the value of the following parameters: the PSR, the SNR per bit of user p in a multi-user reception, denoted E_{b_p}/N_0, the time difference τ, and the frequency shift Δf between the two received signals.

D. Loss Factors

We start assuming perfect parameter estimation. We define a performance indicator: the loss factor δ_p (see Fig. 1). In

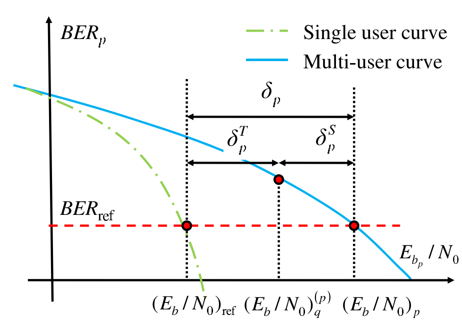

Fig. 1. Loss Factors on Bit Error Rate (BER) Curves, BER_p being the BER associated with user p.

a multi-user scenario, the SNR per bit $(E_b/N_0)_p$ required to achieve a BER_{ref} performance, is inevitably higher than $(E_b/N_0)_{\text{ref}}$, and the difference between these two values is the loss factor δ_p. So, we have that

$$\delta_p(\text{dB}) = (E_b/N_0)_p(\text{dB}) - (E_b/N_0)_{\text{ref}}(\text{dB}) \tag{3}$$

In addition, we define the ratio $(E_b/N_0)_q^{(p)}$ as the required SNR per bit on signal q to achieve a successful decoding on user p. So, from (3), we have that

$$\begin{aligned}\delta_p(\mathrm{dB}) &= [(E_b/N_0)_p(\mathrm{dB}) - (E_b/N_0)_q^{(p)}(\mathrm{dB})] \\ &+ [(E_b/N_0)_q^{(p)}(\mathrm{dB}) - (E_b/N_0)_{\mathrm{ref}}(\mathrm{dB})]\end{aligned}$$

We define δ_p as the product of two terms δ_p^S and δ_p^T such that

$$\begin{aligned}\delta_p(\mathrm{dB}) &= \delta_p^T(\mathrm{dB}) + \delta_p^S(\mathrm{dB}) \\ \delta_p^T(\mathrm{dB}) &= (E_b/N_0)_q^{(p)}(\mathrm{dB}) - (E_b/N_0)_{\mathrm{ref}}(\mathrm{dB}) \\ \delta_p^S(\mathrm{dB}) &= (E_b/N_0)_p(\mathrm{dB}) - (E_b/N_0)_q^{(p)}(\mathrm{dB})\end{aligned} \quad (4)$$

The δ_p^T term is the ratio between the required SNR per bit on signal q to achieve a BER_{ref} performance on signal p and the required SNR per bit in the single user case to achieve the same BER. The δ_p^S term is the ratio between the required SNR per bit on signal p and the required SNR per bit on signal q to achieve a BER_{ref} performance on signal p. According to the definition of the PSR in (2), we have that

$$\delta_p^S(\mathrm{dB}) = \begin{cases} +PSR(\mathrm{dB}), & \text{if } p=1, q=2 \\ -PSR(\mathrm{dB}), & \text{if } p=2, q=1 \end{cases}$$

If $p = 1$ in the scenario presented in Fig. 1, the δ_p^S factor being positive, we can infer that the PSR is lower than one and the received energy for user 2 ($q = 2$) is higher than the one received for user 1.

Similar definitions can be obtained for the loss factors related to user q. Namely, we have that

$$\delta_q^T(\mathrm{dB}) = (E_b/N_0)_p^{(q)}(\mathrm{dB}) - (E_b/N_0)_{\mathrm{ref}}(\mathrm{dB})$$

Now we use these definitions in order to design tests. These tests allow us to know whether the receiver can successfully demodulate one or two users.

III. Performance Indicator

A. Definition

We define the performance indicator Δ_p as

$$\Delta_p(\mathrm{dB}) = \delta_q^T(\mathrm{dB}) - \delta_p(\mathrm{dB})$$

So we have that

$$(E_b/N_0)_p^{(q)}(\mathrm{dB}) = (E_b/N_0)_p(\mathrm{dB}) + \Delta_p(\mathrm{dB}) \quad (5)$$

According to (5), when user p achieves a BER_{ref} performance with an SNR per bit of $(E_b/N_0)_p$, the performance indicator Δ_p represents the additional value that must be added on the SNR per bit $(E_b/N_0)_p$ to achieve a BER_{ref} performance on user q. We study the performance issues according to the value of Δ_p.

When the SNR per bit on user p is set to $(E_b/N_0)_p$, user p is successfully demodulated. Moreover, when the performance indicator $\Delta_p(\mathrm{dB})$ is positive, (5) indicates that the SNR per bit on user p should be higher to successfully demodulate user q. So only one user is recovered in this context (user p). Inversely, when the SNR per bit on user p is set to $(E_b/N_0)_p^{(q)}$, user q is successfully demodulated. Using (5), we have that the required SNR per bit to successfully demodulate user p is lower than the one required to successfully demodulate user q. So both users are successfully demodulated. Similar results are obtained for negative values of $\Delta_p(\mathrm{dB})$ (see Table I).

TABLE I
SUCCESSFULLY DEMODULATED USERS AS A FUNCTION OF THE PERFORMANCE INDICATOR

	$BER_p \leq BER_{\mathrm{ref}}$	$BER_q \leq BER_{\mathrm{ref}}$
$\Delta_p(\mathrm{dB}) > 0$	p	p and q
$\Delta_p(\mathrm{dB}) < 0$	p and q	q

The calculation of the performance indicator $\Delta_p(\mathrm{dB})$ relies on the BER curves for both users p and q. From the BER curve of user q, we get the loss factor δ_q. From (4) and the fact that the δ_q^S ratio equals the PSR or the inverse PSR, we get δ_q^T. Form the BER curve of user p, we get the loss factor δ_p, and $\Delta_p(\mathrm{dB})$ is obtained using (5).

B. Simulation Results

The results presented here are based on computer simulations. Fig. 2 presents the performance of an ARGOS SIC receiver with $K = 2$, $p = 1$ and $q = 2$. Three factors are plotted: $\delta_p(\mathrm{dB})$, $\delta_q(\mathrm{dB})$, and $\Delta_p(\mathrm{dB})$. Perfect parameter estimation is assumed at the receiver. The loss factors and the performance indicator are plotted as a function of the relative time difference τ/T between the two users, for a PSR of 3 dB and a relative frequency shift $\Delta f/R_b$ of 0.125, where R_b denotes the data symbol rate. The reference BER, BER_{ref}, is set to 6.10^{-3} and the corresponding value for the received SNR per bit $(E_b/N_0)_{\mathrm{ref}}$ is set to 5 dB. Since the performance indicator $\Delta_p(\mathrm{dB})$ has always a positive value for all values of τ/T, the satellite successfully demodulates both users when user q is successfully demodulated. From Fig. 2, we have that the multi-user reception induces a loss factor $\delta_q(\mathrm{dB})$ on the reception of user q with a maximal value of 4 dB. So, according to (3), the required SNR per bit in order to successfully demodulate user q is 9 dB (4 dB from the loss factor and 5 dB from the reference SNR per bit). According to the value of the PSR (3 dB), the required SNR per bit on user p is 12 dB. So with these values, the successful demodulation of both users is guaranteed for the given PSR

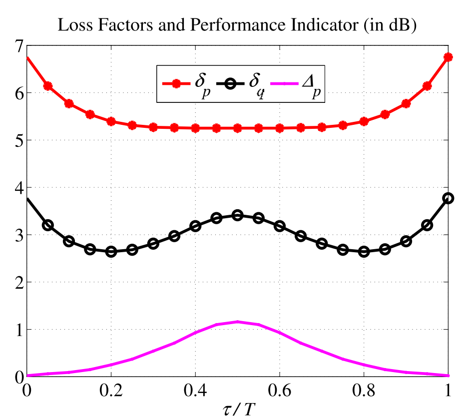

Fig. 2. Loss Factors and Performance Indicator for BER = 6.10^{-3}, PSR = 3 dB, and $\Delta f/R_b = 0.125$.

and all the values of the relative frequency shift. In a similar way, when we fixed the received SNR per bit for user q to 8 dB, which is 3 dB above the threshold value of 5 dB, user q is successfully demodulated for a relative time difference in the following time intervals : $[0.1T, 0.38T]$ and $[0.6T, 0.88T]$. These time intervals represent 56% of the total interval. The results for several values of both the relative time difference and the relative frequency shift are plotted in Fig. 3 and Fig. 4. The SNR per bit on user q has been set to 9 dB, which is 4 dB higher than the threshold. In Fig. 3 and Fig. 4, the

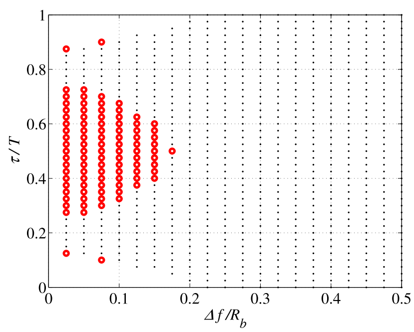

Fig. 3. Areas of successful demodulation for PSR = 3 dB and $E_{b_q}/N_0 =$ 8 dB.

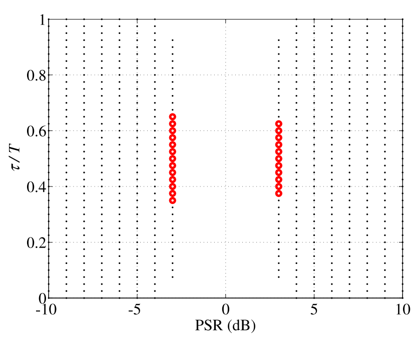

Fig. 4. Areas of successful demodulation for $\Delta f/R_b = 0.125$ and $E_{b_q}/N_0 = 8$ dB.

dots "." denote the cases in which both users are successfully demodulated. The circles "o" denote the cases in which only one signal is successfully demodulated. When there is no marker, none of the two signals is correctly received. These figures provide interesting information since they indicate the ranges of values for which the system is operational. In order to successfully demodulate both users with a frequency shift greater than or equal to 0.2 R_b, Fig. 3 shows that an E_{b_q}/N_0 of 8 dB is required on the weak signal. Moreover, the two users powers should be separated by at least a value of 3 dB. These values guarantee also a successful demodulation over a full range of time difference between the two users. Similarly, Fig.4 shows that when the two user powers are separated by at least a value of 4 dB, a value of E_{b_q}/N_0 of 8 dB on the weak signal guarantees a successful demodulation of both users with a frequency shift between the two users greater than or equal to 0.125 R_b. In this case, the full range of time difference is covered.

IV. Impact Study of Imperfect Parameter Estimation

In this section, we consider imperfect parameter estimation. First, we assume that user p is the user with the strongest received power. We now study the impact of imperfect parameter estimation of user p on the demodulation of user q. The reference SNR per bit $(E_b/N_0)_{\text{ref}}$ on user q ($q \in [1, K]$) that is required in order to achieve a reference BER is now degraded by a factor δ_q^ϵ. This loss factor takes into account both the loss factor δ_q due to the multi-user reception and the loss factor ϵ_q due to imperfect parameter estimation on the strongest signal p. The new value for the required SNR per bit is now denoted $(E_b/N_0)_q^\epsilon$. The upper script ϵ denotes the presence of an estimation error. According to previous definitions, we have that

$$(E_b/N_0)_q^\epsilon(\text{dB}) = (E_b/N_0)_{\text{ref}}(\text{dB}) + \delta_q^\epsilon(\text{dB})$$

Moreover, we have that

$$\delta_q^\epsilon(\text{dB}) = \delta_q(\text{dB}) + \epsilon_q(\text{dB})$$

From these definitions, we have that

$$\epsilon_q(\text{dB}) = (E_b/N_0)_q^\epsilon(\text{dB}) - (E_b/N_0)_q(\text{dB}) \qquad (6)$$

Now, we consider imperfect estimation of both the signal amplitudes, and the time delays on the signal with the strongest received power (user p). The estimation error on the signal amplitude $\epsilon_A^{(p)}$ and the estimation error on the time delay $\epsilon_\tau^{(p)}$ for user p can be written as

$$\epsilon_A^{(p)} = \frac{\hat{A}_p - A_p}{A_p} \qquad \epsilon_\tau^{(p)} = \frac{\hat{\tau}_p - \tau_p}{T}$$

where $\hat{A}_p$ and $\hat{\tau}_p$ denote respectively the estimate of the signal amplitude A_p and the estimate of the time delay τ_p for user p, with $p \in [1, K]$.

In the context of a SIC receiver, the performance achieved on the weakest signal (user q) depends on the estimation performed on the strongest signal (user p). The impact of imperfect parameter estimation on the performance of the weakest signal is studied as a function of the estimation errors on the strongest signal. So we should study the dependence of $\epsilon_A^{(p)}$ and $\epsilon_\tau^{(p)}$ on ϵ_q. We now present the additional loss factor $\epsilon_p(\text{dB})$ presented in (6) for $p = 1$ and $q = 2$. The additional loss factor is plotted as a function of the amplitude estimation error $\epsilon_A^{(p)}$ (for $\epsilon_\tau^{(p)} = 0$) in Fig. 5 and as a function of the time delay estimation error $\epsilon_\tau^{(p)}$ (for $\epsilon_A^{(p)} = 0$) in Fig. 6. The different curves on each figure correspond to different time delay values. From Fig. 5, the estimation error of the signal amplitude on user p can be compensated for all the possible time delays, provided that a 0.8 dB margin is added to the received SNR per bit on user q. This margin covers a 30% error on the signal amplitude. Moreover, when an estimator achieves a precision of 15% on the signal amplitude, the additional loss factor is limited to a factor of 0.2 dB for all the time delays.

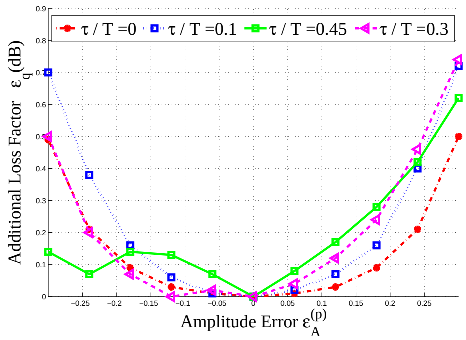

Fig. 5. Additional loss factor due to imperfect amplitude estimation for BER = 6.10^{-3}, PSR = 3 dB, and $\Delta f/R_b$ = 0.125.

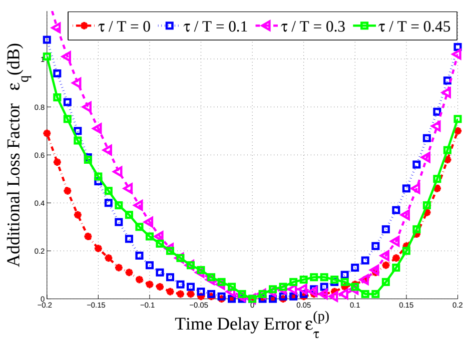

Fig. 6. Additional loss factor due to imperfect time delay estimation for BER = 6.10^{-3}, PSR = 3 dB, and $\Delta f/R_b$ = 0.125.

Thus, it can be stated that ARGOS SIC receivers are robust to imperfect amplitude estimation.

From Fig. 6, the estimation error of the time delay on user p can be compensated for all the possible time delays, provided that a 1.3 dB margin is added to the received SNR per bit on user q. This margin covers a 20% error on the time delay. Moreover, when an estimator achieves a precision of 10% on the time delay, the additional loss factor is limited to a factor of 0.3 dB for all time delays. Compared to the previous case, ARGOS SIC receivers are more sensitive to imperfect time delay estimation.

Fig. 7 shows the impact of an amplitude estimation error on the areas of successful demodulation which was presented in Fig. 3. The results are obtained for an SNR per bit on user q, E_{b_q}/N_0, of 8 dB and a PSR of 3 dB. The left side of Fig. 7 shows the results when perfect parameter estimation is assumed, while the right side is plotted for an amplitude estimation error $\epsilon_A^{(p)}$ of 0.3 (and for $\epsilon_\tau^{(p)} = 0$). The amplitude estimation error on the strongest signal p induces an increased BER on the weakest signal q. So, on the right side of Fig. 7 there are less dots "." identifying the cases for which both users are successfully demodulated. Now, in order to successfully demodulate both users with a 30% error on the signal amplitude, the required $\Delta f/R_b$ should be greater than or equal to a value of 0.3 whereas the value required assuming perfect estimation was of 0.2. In order to keep operating with

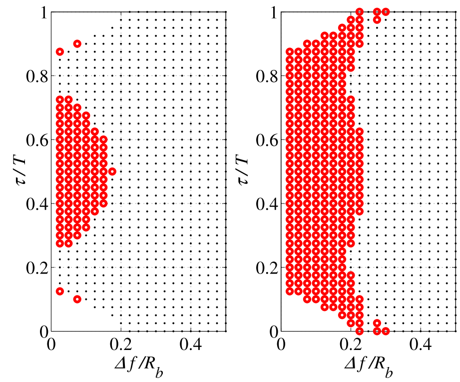

Fig. 7. Areas of successful demodulation for PSR = 3 dB (left side: perfect parameter estimation, right side: imperfect amplitude estimation with $\epsilon_A^{(p)} = 0.3$).

relative frequency shifts greater than 0.2, a 0.8 dB margin must be added to the received SNR on user q (see Fig. 5). Note also that the white area is still unchanged due to the assumption of perfect parameter estimation during the demodulation of the strongest signal.

V. Conclusion

In this paper, we study the performance of ARGOS SIC receivers. We analyze the received SNR per bit and derive performance graphs that show the parameter ranges over which a successful demodulation of all users is possible. First, the graphs are derived in the context of perfect parameter estimation. Then, imperfect parameter estimation is considered. The erroneous parameter estimation affect the estimation of both the signal amplitude and the signal time delay. Carrier frequencies are assumed to be accurately measured by the receiver. ARGOS SIC receivers have been shown to be both robust to imperfect amplitude estimation and sensitive to imperfect time delay estimation.

Carrier frequency estimators should be now considered in order to complete this study. This estimation step actually involves two parameters: carrier frequency and carrier phase. All the estimation steps will be included in the design of a complete ARGOS receiver. This part is left for future work.

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